PILOTED ENTRIES INTO THE EARTH'S ATMOSPHERE

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INTRODUCTION

This paper summarizes research conducted at the Langley Research Center of the National Aeronautics and Space Administration on the requirements of stability, control, deceleration, and piloting techniques necessary for a controlled descent from orbit into and through the earth's atmosphere. The talk is based on (Basis for the talk are) studies made by the NASA on methods of trajectory control and on the simulation of several proposed satellite vehicles during entries using a static simulator at the Langley Research Center and the 50-foot human centrifuge at the (1) Aviation Medicine Acceleration Laboratory, Johnsville, Pennsylvania.

Most of the research in this paper is concerned with a type of trajectory which may be called a "high-drag variable-lift trajectory." For this type of trajectory the satellite vehicle produces a large wave drag and a small lift as it passes through the atmosphere. By controlling the amount of lift, the trajectory and hence the deceleration, the heating, and the distance traveled (range) can be controlled.

This type of trajectory is used because it is particularly beneficial in minimizing the total heat input to the vehicle. As shown by the analysis of Allen (ref. __), the heat input is directly proportional to the ratio of skin friction to total drag of the vehicle. By keeping the total drag high, the time required from the point of entry into the atmosphere to the point of landing is relatively short. By varying the lift to small positive or negative values, the pilot of the vehicle can control his rate of descent to correct for past errors in navigation and land at the desired place on the surface of the earth.

High-drag variable-lift trajectories may be used by capsule type vehicles and by winged vehicles which enter the atmosphere at high angles of attack, In figure 1, two typical vehicles of this class are shown in the upper left and center of the figure, while in the upper right is pictured a capsule of the glide type which will be discussed later in the paper. In figure 2, the variations of drag, lift, and pitching-moment coefficients with angle of attack are shown for the winged vehicle whose center of gravity is located at the centroid of area of its plan form. The region of interest lies between angles of attack of 60° and 120°. In this region, the winged vehicle has maximum drag and a negative lift curve slope with zero lift at 90°. In this region of interest, the capsule shown in the upper left of figure 1 also has identical variations except that on the capsule we define as zero angle of attack that angle where the lift is zero. Wind-tunnel data show that both configurations have a linear, stable variation of static stability (C_{m_α}) over an angle-of-attack range of ±30° from trim.

Following the entry, the capsule must deploy a parachute for a controlled landing. The winged vehicle, on the other hand, must be capable of pitching from the high-drag to a low-drag condition at a subsonic or supersonic Mach number and glid~~e~~ing to a conventional landing with a good lift-drag ratio. ~~Such a thing can be accomplished but is not within the scope of this paper.~~ The transition to the low angle of attack condition would require some variable-geometry feature to shift the aerodynamic center rearward.

Utilizing these trajectories and simulating these vehicles, some feel for the problems associated with piloted entries into the earth's atmosphere has been obtained and are summarized herein.

TRAJECTORY CONTROL

Allen and Eggers have shown (ref. __) that bodies entering the atmosphere with high drag and zero lift attain decelerations which reach at least 8g (if one uses their exponential variation of atmospheric density*). Such decelerations represent very nearly the upper

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*Between entry angles of 0° and 1.0°, ARDC atmosphere gives peak decelerations of about 7.4g from an average north-south orbit, about 1g less on a west-to-east entry, and about 1g more on an east-to-west entry.

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limit of man's capabilities without excessive protection devices and severely limit the entry conditions of the vehicle. With very small values of L/D, large reductions in deceleration can be obtained over a range of entry angles as has been shown by Chapman in reference 2. Such trajectories lead, however, to skips which are not necessary for the reduction of deceleration and are detrimental to heating and to the prediction of distance that will be traveled. It would therefore seem logical to explore the intermediate region in which the lift-drag ratio is varied in accordance with considerations such as range or heating or deceleration while still maintaining high drag.

It is interesting to find that there are certain families of high-drag variable-lift trajectories in which one of the trajectory variables can be held constant during the entry. Of these, constant deceleration and constant rate of descent (rate of change of altitude) have proven most useful. We will consider the latter briefly.

One of the more important parameters in the prediction and control of range and deceleration is the rate of descent (rate of change of altitude). Rate of descent is the product of the velocity (V) and the sine of the flight path angle (γ)

$$\dot{h} = V \sin \gamma$$

For any trajectory, the maximum deceleration that can be measured in the direction of the velocity occurs when the product of the velocity and rate of descent are a maximum, namely

$$a_n \sin \alpha)_{max} = a_V)_{max} = \frac{\dot{h}V}{C}\left(1 + \frac{C}{V^2}\right) \quad , \text{ g units}$$

where C is a constant on the order of 1.48×10^6 (ft/sec)^2. Strangely enough, when the rate of descent is held constant throughout a trajectory, the maximum deceleration always occurs when the velocity is about 0.51 of its value at entry. For near circular orbit, entry velocity is just under 26,000 feet per second and we find that the maximum deceleration is directly proportional to the rate of descent only

$$a_n \sin \alpha)_{max}, \text{ g units} = \frac{4}{450}\,\dot{h}(\text{ft/sec})$$

$$= 4\, \gamma_o \text{ (deg)}$$

or about four times the equivalent entry angle (γ_o).

In figure 3, data are presented for the winged vehicle for four trajectories in which the rate of descent is held constant throughout the entry. The time scale starts when the vehicle passes through an altitude of 350,000 feet with a velocity just under 26,000 feet per second. The four trajectories shown represent initial flight path angles of 1.0°, 1.5°, 2.0°, and 2.5°. The rates of descent corresponding to these conditions go from 450 to 1125 feet per second in even increments of 225 feet per second and these rates of descent were held throughout the entry by changing the angle of attack of the winged vehicle in the manner shown in the figure. Times to enter took from 4 to 9 minutes. Until the very end of the trajectory, relatively small, slow changes in angle of attack are required and it can be seen that maximum acceleration in each case is about four times the entry angle.

The point to be made here is that maximum deceleration can be predicted as a function of rate of descent. If rate of descent can be measured and displayed to the pilot, the pilot may well be able to maintain or change his rate of descent to a more desirable value which may be determined from range or deceleration considerations. For example, between maximum decelerations of 4 and 10g, the pilot has a variation in range of roughly 900 miles.

Heating rates and temperature effects

The relative effects on heating and temperature for high-drag lifting trajectories as compared with high-drag - zero-lift (ballistic) trajectories are shown in the next figure. The data of figure 4 show the deceleration, heating rate per unit area, and skin temperature at the stagnation point as calculated for two entry trajectories of the winged vehicle: one where angle of attack is held constant at 79°, the other where angle of attack is 90° (zero lift). The entry angle in both cases is 1°. The data for the zero lift trajectory may be compared with that of Eggers and Allen (ref. 1) for high-drag blunt bodies.

As shown in the upper part of the figure, the maximum deceleration for this small entry angle was reduced from 8g to 3-1/4g by reducing the angle of attack 11°. As a result of this reduction in angle of attack, the range was increased by 573 miles. For these two angles of attack, the laminar stagnation-point heat-transfer rates per unit area Q/A were obtained by the method of Romig (ref. 3) for a vehicle with 200 square feet of exposed area. These calculations were made throughout the trajectory, starting at 550,000 feet where the heating rate was essentially zero, although the data of this figure start at 350,000 feet. The temperature of the vehicle during the entry will depend on its structure and heat protection. However, for a comparison, a ~~unit~~ area of 1/8 inch thick berillium located at stagnation point and free to radiate from one face with an emissivity factor of 1.0 was used to calculate the stagnation-point temperature for these and many other entries. Qualitatively, the data of such trajectories show that a reduction in angle of attack has little effect on the maximum temperature obtained but significantly reduces the heating rate at the stagnation point.* The total heat which

*This effect is due to the reduced rate of descent, since the data were calculated for the stagnation point regardless of how that point moved due to a change in angle of attack.

must be absorbed or dissipated, as measured by the area under the heat-transfer rate curves, is increased by holding a lower angle of attack.

Deceleration control

If, during an entry, deceleration and time were the primary factors, a most efficient method of dissipating energy would be to determine an acceptable level of deceleration and control the trajectory such that this deceleration is obtained and held to that value as long as it is practical. With the specific requirement that a deceleration controller must be adaptable to a "band" of entry conditions, studies have been made on methods of controlling the deceleration as a function of quantities that can be measured from the vehicle during an entry.

In making such studies, one thing that becomes quite obvious is the lag in time between the production of lift and the change in the quantity to be controlled. This is because most of the important variables can be controlled only through changes in the flight path. At low dynamic pressures, changes are slow; at high dynamic pressures, the reverse is true. Thus it is usually not sufficient to control a variable but you must generally control the rate of change of that variable. The result of such control can be considered anticipation or damping, depending upon what part of the trajectory you are considering. Regardless of what variable is being measured, in almost all cases this effective rate control reduces to a measure of the rate of change of dynamic pressure (change in density and change in velocity).

Rate of descent, discussed earlier, is a quantity which it is felt must be measured or calculated during an entry and can be used directly for deceleration control. Accuracy is not particularly critical and the angle of attack of the vehicle, without being known exactly, can be changed in the correct direction to maintain or change rate of descent.

However, an automatic control which operated on this basis would overshoot and "hunt" if the desired rate of descent differed greatly from the measured value, whereas a human pilot could damp out such oscillations. To prevent this automatically may require calculation of $\ddot{h}$.

One method that provided good automatic deceleration control over a range of entry angles was found by controlling the angle of attack as a function of measured deceleration and computed rate of change of deceleration. Rate of change of deceleration was used to provide the necessary lead or anticipation. As an automatic control, the device controlled the angle of attack such that

$$\Delta\alpha = \alpha - \alpha_{trim} = K_1 a_n + K_2 \dot{a}_n$$

where a_n is the normal deceleration measured along the z-axis of the vehicle, and $\dot{a}_n$ was calculated from measured values of V, $\dot{V}$, $\dot{h}$, and a_n. It can be shown that rate of change of deceleration need not be measured and, in fact, better results can be obtained if it is calculated from the expression*

$$\dot{a}_n = a_n \left(2 \frac{\dot{V}}{V} - \frac{\dot{h}}{H} \right)$$

*Here $a_n = \frac{C_F(\alpha)}{2W/S} \rho(h) V^2$ where $C_F(\alpha)$ is the resultant force coefficient but is treated as a constant in order to filter out high-frequency changes in angle of attack.

In our calculations H was a constant which best fitted the relation $H = -\rho \frac{dh}{d\rho}$ throughout most of the trajectory, but could be a programed

function of h or ρ if desired and if these quantities could be (1)
accurately measured from the vehicle. It is thought that V, $\dot{V}$, $\dot{h}$, and a_n will be more easily measured than, for example, the flight path (2)
angle, γ, and its rate of change, $\dot{\gamma}$. Likewise, angle of attack, α, in all likelihood will have to be a calculated function. (3)

With the intention of limiting the deceleration to the vicinity of 3g, the constants $K_{1,2}$ were determined from the data of figure 3 for (4)
the winged vehicle. Figure 5 shows the time histories of deceleration, rate of descent, and angle of attack for this vehicle for entries of 1°, 2°, and 3° where the constants $K_{1,2}$ used in the controller were the same for all entry angles.

The lead or anticipation effect of the $K_2\dot{a}_n$ term can be seen in this figure to be quite effective in holding the deceleration to the desired value.

Smaller rates of change of angle of attack are required if this type of controller is used with the vehicle pretrimmed to some lower angle of attack, say 84° for the winged vehicle and -6° for the capsule.

Range control

Perhaps the most apparent need for trajectory control outside of that necessary for human or structural survival is that of having the landing occur at a specified place. In this paper only the range traveled along the flight path is considered. ~~Because the reentry will probably~~ be made without power ~~and hence~~ any adjustments that are necessary in the range must be made by varying the lift and drag forces. For the high-drag variable-lift type of vehicle previously described, the range that will be traveled during a reentry can be calculated as a function of the initial conditions for the case where the L/D is maintained constant by holding a constant angle of attack. Figure 6 summarizes the range capabilities as a function of angle of attack and reentry angle for a typical reentry velocity and wing loading. The figure indicates the variation in range possible by holding different angles of attack for each reentry angle and can be used to determine the angle of attack needed to obtain a given range. Insert * ~~However, the means of obtaining desired range is open loop and therefore any uncertainties of flight path angle, initial range-to-go, velocity, density variation, etc., lead to errors in the actual range obtained.~~ For example, if the initial flight path angle were 1-1/4° rather than 1° and we wanted to travel 2000 miles, our range error would probably be around 150 miles. It is desirable then that some type of continuous control be applied based upon the progress of the trajectory. As one approach to this problem, ~~we have made~~ theoretical studies have been made based upon the concept of controlling the reentry to a reference trajectory that terminates at the desired destination. The assumption has been made that, during the atmospheric portion of the trajectory, means will be available for an accurate measurement of the position of the vehicle with respect to the desired destination. This might be done by on-board inertial navigation equipment or by ground tracking stations. In essence, the range-to-go must be a measured or computed quantity. By continuously comparing the actual range-to-go with the reference range-to-go, an error signal is obtained. The magnitude of this error signal coupled with the rate of change of the error signal is then used to command an angle of attack that causes the trajectory to approach the reference. The equation for the command angle of attack is of the form

$$\alpha_D = \alpha_T + K_1 \, \varepsilon_{RTG} + K_2 \, \dot{\varepsilon}_{RTG}$$

where α_T is the desired trim angle of attack.

Results have shown that this approach is effective in controlling the range. As an example, figure 7 shows the computed altitude-range profile for two controlled trajectories which enter with an angle of -1° but with initial ranges-to-go to the desired destination that differ by 500 and -200 miles from the reference trajectory. Both trajectories show smooth correction to the reference with only small overshoots and at an altitude of 100,000 feet are within 10 miles of the reference. Runs have been made where ~~straight-line approximations of~~ the reference trajectory ~~were utilized~~ with no apparent decrease in terminal accuracy.

The trajectories that are presented in figure 7 were calculated on the basis of a nonrotating earth and atmosphere. However, the effect of these factors on the range and trajectory has been calculated ~~and can be easily incorporated in the form of a contraction-expansion factor.~~

Static simulation

The application of the described trajectory control methods in cases where the human pilot is performing the control task has been studied using a static simulator. In this simulator, the equations of motion describing the trajectory and the short-period dynamics of the vehicle are solved on an analog computer which is electronically coupled with a cockpit wherein sits the pilot. An instrument display of the important trajectory and attitude parameters and a side-arm controller ~~is~~ are available to the pilot for his control function. Figure 8 shows the layout of the cockpit and one of the side-arm controllers that was used. (Some detail on the instrumentation and the controller will be needed here.) The preliminary tests were concerned with determining suitable arrangements of the instruments and desirable variations of stability and control effectiveness. A discussion of some of the interesting aspects of stability and control will be presented later. For the present, the application of the simulator to range control will be considered.

Range control with on-board equipment

The principle involved in the theoretical studies of range control, that is, controlling to a reference trajectory, was applied to the pilot-controlled case by comparing the computed desired angle of attack with the actual angle of attack in order to obtain an angle-of-attack error. This signal was used to actuate the zero reader instrument shown previously in the photograph of the pilot's instrument panel. The pilot's task during the run was to maintain control over the attitude of the vehicle and to control angle of attack in accordance with the indication of the zero reader. Runs that have been made have indicated that there is slightly more of a tendency to overshoot the reference trajectory with the pilot in the loop possibly due to his tendency to lag slightly behind the indicators of the zero reader. However, the accuracy in reaching the desired destination was only slightly less than in the theoretical studies.

Another approach to the problem of trajectory range control has embodied control procedures somewhat similar to the GCA methods in current use for airplane landing approaches during instrument weather. In this approach, the "GCA operator" is located at a ground station and has a presentation of the position of the vehicle with respect to the desired landing position. By establishing a desired flight path to be flown into the destination, the controller has a reference to which to control the trajectory just as in the previous cases. (1)

The procedure followed is illustrated on figure 9 where the circled numbers indicate the angle-of-attack commands which were spoken to the pilot ~~given~~ by the GCA controller. As a reentry progresses below the initial altitude of 350,000 feet, the ground observer compares the range with that of the reference trajectory and determines angle-of-attack commands that will correct the trajectory over to the reference. In performing this function, the GCA controller also has graphs relating range, angle of attack, and flight path angle such as was shown previously in figure 6 to aid him in predicting the effectiveness of a certain command in correcting the trajectory to the reference. By continuously observing the effect of his angle-of-attack commands, the controller (with some experience) is able to periodically issue angle-of-attack commands that will bring the trajectory closer into line with the reference. It has been found that an experienced operator can consistently control a reentry to within 10 miles of the desired destination as long as the initial conditions are such that the desired range can be reached without continuously operating at the angle-of-attack limit.

Tests have been made where the problem of the GCA operator has been complicated as by applying noise on the X-Y recorder in such a way as to simulate radar tracking noise. In still other tests, the density altitude relationship has been arbitrarily changed (unknown to the GCA operator) by as much as a factor of 2. These factors, taken separately, increased the terminal errors by small amounts although the accuracy was usually within 20 miles. When taken in combination, however, the problem of GCA control became more difficult and the errors increased to as much as 60 miles.

Tests were also made of the pilot's ability to perform as his own controller by observing a relatively small plot of the altitude range profile as presented in the previous figure. It was found that with sufficient indoctrination, the pilot could satisfactorily determine for himself the proper angle-of-attack variation so as to cause the trajectories to terminate at the desired location. It is necessary, however, that the stability of the vehicle be good enough that the pilot can divert some of his attention away from the attitude instruments and toward the range display.

DYNAMIC SIMULATION PROGRAM

General

In conjunction with the range control studies just described, an extensive program to determine the capabilities and limitations of human pilots during atmospheric entries was performed using the fixed base simulator at the Langley Research Center and the 50-foot human centrifuge at the Navy's Aviation Medicine Acceleration Laboratory, Johnsville, Pennsylvania. Three proposed satellite vehicles, each producing a different g-field on the pilot, were simulated in these tests, and ten pilots (Navy, Air Force, Marine Corps, and NASA) participated.

In order to give the results of this program, it is necessary first to briefly describe the vehicles simulated and the cockpit equipment used in the program.

Characteristics of Simulated Vehicles

The three vehicles simulated were shown in figure 1. In the capsule shown in the upper left of figure 1, the pilot sat facing backward with his instrument display showing all angular displacements as though he were flying a conventional airplane which was moving in the direction of his line of sight. To the pilot, the capsule therefore had an apparent positive lift-curve slope. G-forces were from chest to back (positive longitudinal). This capsule has good static stability (as shown by instrument tests) in pitch and yaw, but none in roll. Damping (defined herein as a moment resisting an angular velocity) about all three axes was varied from zero to good on different entries. Various amounts of aerodynamic and reaction controls were included. Aerodynamic controls on this capsule could consist of lateral and longitudinal flaps which are deflected into the wind and add to the frontal area of the vehicle.

In the winged vehicle, the pilot sat in a normal flying position and was exposed to positive normal accelerations (head to feet) throughout the entry. True attitude angle and angle of attack were displayed to him so that the negative lift-curve slope of the vehicle was quite apparent to him. The winged vehicle at 90° angle of attack had static stability in pitch and roll but zero static stability in yaw. As with the capsule, various amounts of dynamic stability and aerodynamic control effectiveness were investigated and reaction controls were included for control at low dynamic pressures. The third vehicle simulated did not have exactly the high-drag - low-lift characteristics of the first two but did have other characteristics of interest which help to broaden the investigation. This vehicle is shown in the upper right of figure 1. The pilot faced forward in this vehicle, looking along his flight path. At trim, the L/D was 0.5 and the pilot was subjected to a combination of negative longitudinal (back to chest) and positive normal as indicated in figure 1. At high angles of attack these decelerations were about evenly divided; at low angles of attack, the deceleration was purely longitudinal. The vehicle had a small positive lift-curve slope up to about 15° angle of attack but angle of attack primarily affected the drag and deceleration rather than the lift and flight path.

Controls

The aerodynamic controls and the jet reaction controls were operated by the pilot through one control stick and one set of rudder pedals. Displacement of the pilot's controls produced proportional moments from both sources. The aerodynamic control moments were proportional to the dynamic pressure while the reaction control moments were independent of dynamic pressure. Neither lags nor dead spots were simulated.

The pilot was provided with a side-located control stick for pitch and roll control. Two side-located control sticks were used at different times during the simulation programs. The first series of tests was made with a spring-loaded side-arm control grip which was designed to mechanically position hydraulic control valves. The effective pivot point in both pitch and roll was in the wrist. A photograph of this controller is shown as an insert in figure 8.

The second series of tests was made with a small "pencil-type" control stick also located at the end of the pilot's right arm rest. This controller can be seen in figures 9 and 10. Designed for electronic control systems, the stick was spring-loaded and had no intentional friction. The design was a refinement of the side-located controller reported in reference 4 which has been flight tested over a period of several years by the NASA.

Both controllers were designed with the purpose of allowing the pilot to operate his aerodynamic controls during high deceleration conditions both steady and oscillatory.

Instrument display

An instrument panel with nine operative instruments was provided the pilot for both static and dynamic simulations. A photograph of this instrument display during operation of the static simulation is shown in figure 8. From left to right the four instruments across the top give the four trajectory variables: acceleration, rate of descent, altitude, and velocity. The second row of three instruments gives the longitudinal attitude information: angle of attack, pitch angle (indicated on a rotating ball generally referred to as "eight ball"), and angle-of-attack error meter used for deceleration and/or range control information. The eight ball also displays roll angle and directly below the eight ball, yaw angle is indicated and below that is shown angle of sideslip. For the vehicles investigated to date, sideslip has not been critical and its display has therefore been relegated to a minor position on the display. The other instruments shown in figure 8 were inoperative.

Tests

The three vehicles just described were physically simulated in the gondola of the AMAL centrifuge. All simulations were made "closed-loop" by simulating the inertial, gravitational, and aerodynamic forces as well as the dynamics of vehicle with the Typhoon computer located at the Aviation Computer Laboratory and electrically connected to the centrifuge by telephone cables. During operations the pilot had direct control over his simulated vehicle and indirect control over the centrifuge. When he moved his controls his instruments indicated the response of the simulated vehicle and the accelerations that would be produced by these motions were fed to the drive mechanism of the centrifuge which, in turn, produced these accelerations. Thus the pilot alone operated the centrifuge through the operations of his cockpit controls. Emergency stop switches were available to the pilot, project engineer, medical officer, and others in the event the pilot lost control of the vehicle and "spun in." A good comprehensive description of the closed-loop operation of the centrifuge was given at the January 1951, meeting of the IAS by Woodling and Clark (ref. 5).

Approximately 360 simulated entries, static and dynamic, were made during a 4-week's period. The vehicles were simulated with five degrees of freedom (no side-force equation) on the computer. The linear accelerations from the two force equations were fed to the centrifuge but the angular accelerations due to angular motions ~~of the vehicle were not since they were small and~~ as impossible to simulate ~~with the correct sense~~ correctly on the centrifuge. Converting from one vehicle to the next was accomplished by rotations of the gimbals and the appropriate computer changes.

Entry angles up to 6° from circular orbits were simulated for the vehicles. The simulated entry of the high-drag - variable-lift vehicles was started at 350,000 feet altitude with the vehicle at a velocity of 25,863 feet per second. The third capsule, having a high wing loading, was started at 275,000 feet with a velocity of 20,700 feet per second (0.8 satellite velocity) to simulate an entry made necessary by the failure of the final boost stage to fire during an attempted launch. Most entries terminated at about 60,000 - 75,000 feet where the velocity was 1300 feet per second. Such trajectories required about 5 to 10 minutes per run.

Prior to "flying" the dynamic simulator, the pilots spent a week flying the static simulator at the Langley Research Center. Early results on this static simulator were later confirmed in the dynamic simulation program. The pilots were indoctrinated as to the characteristics of the vehicle they were to fly and asked to fly various types of trajectories at various conditions of stability and control. Some of these tasks follow.

Tasks

For the two high-drag - variable-lift vehicles, some of the tasks given to the pilots were as follows:

(a) Maintain a constant angle of attack.

(b) Make step changes in angle of attack when decelerations reached a certain level.

(c) Vary angle of attack such as to hold zero error on a zero reader type meter. For this task, the difference between the actual angle of attack and the angle of attack computed by equation 4 was shown to the pilot in the form of an error on a meter. Whenever the meter went off zero, the pilot changed his angle of attack in the opposite direction to return it to zero. By keeping the error small, the pilot controlled his trajectory in a manner similar to the automatic deceleration controller referred to earlier in this paper.

(d) Maintain constant rate of descent.

(e) Change rate of descent from its initial value to some prescribed value and hold it there.

(f) Allow deceleration to build up to but not exceed a certain value and hold it there as long as possible.

(g) For some entries with the capsule, the pilot was given only reaction controls and instructed to control his angular motions only.

For the glide capsule, (a), (b), (d), and (e) were used for early studies but one primary task was used for most of the tests, namely, reduce rate of descent (or flight path angle) to zero or some small value and "bleed-off" velocity at this condition as long as aerodynamically possible.

Variations in stability

Given one of the above tasks, the pilots were required to fly consecutive entries with progressively consecutively less and less damping about all three body axes. Figure 11 shows the variation of the ~~critical~~ damping of a second-order system whose coefficients vary linearly with dynamic pressure. Each point on the curves represents the damping at a corresponding constant* value of dynamic pressure. From a level of dynamic

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*When dynamic pressure is increasing with time, an additional damping is obtained. When dynamic pressure is decreasing, the damping is reduced. See reference 6.

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stability considered acceptable by the pilots (shown on fig. 11 as "standard"), the dynamic stability was reduced in steps of 1/2, 1/4, and 1/8 of that value and then set to zero.

Static stability of the vehicles was obtained from wind-tunnel tests and, in general, was not varied. However, to measure its effect, limited tests were made at 2, 4, 1/2, and 1/4 of the wind-tunnel values. In general, when this was done, the pilot's control power about the corresponding axis of the vehicle was changed proportionally so that trim capabilities of $\pm 30^{\circ}$ were retained. Labeled as "standard," the variation of natural period with dynamic pressure is shown in figure 11 for the high-drag capsule and winged vehicle.

Limited tests on the effects of cross control due to the deflections of the aerodynamic control surfaces were made. Also some tests were made using jet reaction controls only. On-off reaction controls were compared with proportional in several runs but detail studies were not made.

Results

General

Given acceptable ~~and~~ or low values of damping, the pilots could perform all of the tasks with good proficiency. Whether a vehicle had a negative or a positive lift-curve slope did not bother the pilot so long as he knew the characteristics of the vehicle he was flying. The entries were not considered difficult so long as the vehicle had a little natural or artificial damping and performance of tasks did not noticeably deteriorate with increased levels of deceleration until an abrupt complete deterioration occurred. This deterioration varied about ±1/2g between pilots. This break occurred with (1) loss of peripheral vision due to grayout or blackout at about 8 positive normal g, (2) from loss of focus power and pooling of the blood in the hands and feet at 4 to 6 negative longitudinal g, or (3) from inability to breathe (compression of lungs, causing a choking sensation) at 8g of positive longitudinal decelerations. Most tests were made with standard g-suits but for comparison, some tests were made with MC-4 partial pressure suits.

Specific g-fields

Good control under relatively long (1 - 2 minutes) periods of high (6g - 8g) decelerations was exhibited by pilots flying with positive longitudinal or positive normal accelerations acting on them. Some boundaries are shown in figure 12 for regions of good, acceptable and tolerable deceleration forces acting on the pilot from the different quadrants. The boundaries are primarily functions of time. Under positive g (normal and longitudinal), the pilot could tolerate 6g to 8g for periods of time of 1 to 2 minutes while controlling the trajectory and the angular motions of the vehicle. Continuous control between 4g and 6g could be performed from 2 - 6 minutes and below 4g, no limits in time were found and the pilots felt they could fly indefinitely at this condition.

In the positive longitudinal g-field at 8g, the pilots felt that their chests were about to collapse and experienced great difficulty in filling their lungs.* No grayout was experienced. In fact, all but one

*By holding one's breath and keeping the lungs filled, higher g for short periods of time can, of course, be tolerated. The trick is to take a deep breath at the right time.

pilot felt a g-suit did more harm than good in this g-field and did not connect their g-suits for these tests. Some tests with a partial pressure suit indicated a small amount of relief from the sensation in the chest due to the more even distribution of the pressure over the diaphragm.

Positive normal accelerations of 8g represent the upper limit at which a pilot can fly for 1 or 2 minutes and do a good job. At 8g, the pilot is continually on the verge of grayout or blackout and must work to keep his lungs filled. At 6g, there is a great reduction in effort required and below 4g, controlled breathing is not even required.

With a combination of positive, normal, and longitudinal g (resultant g-force acting 45° to the chest), one pilot flew for 100 seconds between 8g and 9g during an entry which lasted about 6 minutes. A combination of positive, normal, and negative longitudinal g was covered in the X-15 programs and this is indicated in figure 12.

When the negative longitudinal g-force becomes larger than the positive normal g-force, the g-field becomes extremely uncomfortable. Negative longitudinal accelerations were the most difficult on the pilots, both physically and supportwise. Accelerations in this field were limited to short periods at 5g due to the pilots' inability to focus their eyes above this g-level (one pilot lost focus power above 3.5g) and the pooling of blood at the ends of their feet and hands. With additions of positive normal g, 4 to 5 total g became tolerable for longer periods of time. An extensive support system was required to keep the pilot secured. Nasal discharges due to the g-field did little to help the pilot's vision of his instruments.

The ratings given to figure 12 may be varied slightly with improved support systems and special devices. The same seat was used by all pilots in all g-fields and it is felt that some improvement in comfort could be achieved by custom tailoring. Additional supports were added in these tests whenever required. For example, for positive longitudinal decelerations, additional neck support was found beneficial and with negative longitudinal g, additional leg, arm, and chin supports were required. Special devices such as ace bandages on the calves of the legs helped to reduce blood pooling in the feet with negative longitudinal accelerations.

Validation

One of the more remarkable results of this program was the comparison of static and dynamic runs. Most of the dynamic runs were immediately preceded or followed by static runs in which the pilot flew the entry without the centrifuge moving. In most cases, the pilot said he felt he did a better job under g (dynamically) than he did statically. In some cases, the pilots flew dynamic runs that they could not fly statically. In these simulations, angular accelerations were negligible compared to the linear acceleration, and were not simulated by the centrifuge, so that motion cues were apparently not the reason. In most entries, piloting errors could produce high decelerations with oscillatory amplitudes and the pilots felt that this produced an incentive for perfection during the dynamic runs. Also steady decelerations produced a steadying (stabilizing) effect on a pilot - a factor which must be experienced to be appreciated.

Tasks

All of the tasks listed earlier could be performed with good proficiency but some tasks required more practice than others. Holding constant angle of attack and making step changes in angle of attack were so easy that they were used only as preliminary or training tasks. Holding rate of descent constant required slightly more attention but posed no difficulty. Changing rate of descent to a new value sometime led to overcontrolling when the entry angle was large but with practice, good proficiency was displayed. If the entry angle were 5°, for example, the pilot, noting his rate of descent, would change his angle of attack to a high lift condition and reduce his rate of descent as rapidly as possible to a value of 400 or 500 feet per second. If ordered to go to, say, 500 feet per second, he sometimes overcontrolled and reduced his rate of descent to, say, 300 feet per second before achieving the desired value.

When the high-drag vehicles were controlled such as to keep the "zero reader" centered, trajectories similar to those of figure 5 were obtained. This method of control worked quite well in serving to train the pilot as to the amount of anticipation required between changes in angle of attack and the effect of these changes on the flight path and deceleration. Whenever the vehicle had very low damping and only slow changes in angle of attack could be made safely, such anticipation was very valuable.

The pilot, instructed to allow the deceleration to build up to a certain value and then hold it at that value, could perform this task surprisingly well for small (up to 2°) entry angles. With increasing entry angles, this became increasingly difficult due to (1) the anticipation required and (2) less time was available for the maximum allowable lift to reduce the rate of descent sufficiently before the desired deceleration is reached. However, the higher the dynamic pressure (and consequently the lift and drag), the quicker was the response in deceleration to a change in the angle of attack.

For the lifting capsule, the primary task described earlier could be accomplished reasonably well after some practice. Since angle of attack primarily affected drag (and deceleration) rather than lift, control of the trajectory required rather large changes in angle of attack but with moderate damping, this task presented no difficulty. Entry angles of 4° were the maximum that could be tolerated.

Dynamic stability

In the first series of tests using the static simulation, the winged vehicle was flown at consecutively lower values of damping. These tests were made using the mechanical side-arm controller described earlier. The pilots were just able to fly the one-fourth standard condition and completely unable to fly the one-eighth standard condition, no matter what the task or entry angle. The records showed that the pilot was inadvertently cross-controlling (moving his side-arm control adversely in roll) pitch when he was attempting to control pitch [illegible] which caused the vehicle to perform a pitch-roll divergence. Since a number of pilots who participated in the ~~X-15~~ static and dynamic simulation program of vehicles ~~last year~~ had experienced the same difficulty using this type of controller, the controller was removed and replaced with the pencil controller described earlier. With this controller, the pilots were able to fly complete entries with one-eighth standard and also with zero damping about all three axes. The latter case required some diligence but could be performed on the winged vehicle, both statically and dynamically, by all pilots. The high-drag capsule could be flown at one-eighth standard damping but only on a very few runs could it be flown through a complete trajectory with zero damping.* With the addition of very small amounts of static stability in roll, the high-drag capsule was very easily controlled at zero damping.

*Again it must be remembered that zero damping means the vectoring moments in roll, pitch, and yaw were set at zero. The effects of negative rate of change in dynamic pressure, however, were present and were destabilizing.

Because of its cross-coupling characteristics at conditions of low dynamic stability, the mechanical controllers in both the static and dynamic simulator cockpits were removed and the electronic pencil-type controller used for all other tests reported herein.

Static stability

With good dynamic stability, changes in static stability had little effect on the pilot's rating so long as his control power was changed a corresponding amount. However, with low values of damping, high static stability was detrimental because of the high frequency, poorly damped oscillations which the pilot had to contend with.

The effects of high, "standard," and low static stability on the variation of the vehicle's natural period with dynamic pressure can be seen in figure 11. High static stability causes very rapid changes from long to short periods during the transition from zero to low dynamic stability. With low damping, this change can be extremely difficult on the pilot who can do nothing with the very short-period oscillation which then exists throughout the entry. (1)

All of the vehicles had essentially no static stability about one axis. If a vehicle had a low moment of inertia about one axis, the lack of static stability was extremely obvious and required continuous attention of the pilot at all times to keep the desired orientation (roll angle for the capsule, yaw angle for the winged vehicle). As pointed out earlier, with zero damping about all three axes of the capsule, it was virtually impossible to fly the entry due to the lack of roll static stability. With the addition of a very small amount of artificial static stability in roll, the pilot had no difficulty in controlling the vehicle. This was found to be true in all vehicles with the effect diminishing with increasing inertia about the critical axis. (2)

Controls

Time does not allow a discussion of control effectiveness factors investigated. However, two small observations may be in order.

A notable improvement in handling qualities of the three vehicles was obtained by putting a grip with the pitch trim wheel in the pilots' left hand. Since they had no throttle or other duties for their left hand, the pilots suggested this modification about half way through the program. Within a few trajectories after the change, the pilots were controlling the vehicle's trajectory with their left hand and the vehicle's angular motions with their right hand and feet. The pilots rated this type of control quite highly, particularly for low stability conditions. The trim knob location can be seen in figure 10.

In all g-fields, the pilots were able to operate their rudder pedals. For the positive longitudinal g-fields of the capsule of figure 1, it was necessary to use stirrups, which can be seen in figure 10, in order to keep the pilot's feet on the pedals. This also was a pilot invention. Although their feet were free to (differentially) translate, the pilots kept their heels essentially fixed and all the necessary pedal motion was obtained by moving the balls of their feet back and forth.

It is hoped that designers, considering the use of three-axis side-arm controllers, will first take a serious look at treddles or lightly loaded rudder pedals for the control of the yaw degree of freedom.

Instruments

In general, it was found that instrument design and arrangement are very critical for flying in high g-fields since a pilot's ability to think and reason under high g-loads is definitely impaired. Instrument scan and comprehension should be made as simple as possible. All needles and gages should move in the correct "instinctive" direction.

In the tests described herein, only angular displacement indications were used. The addition of rate indications for low stability conditions would appear to be advantageous for the critical cases described earlier. However, it may turn out that with very high frequency oscillations, such as were encountered, only marginal improvements will be realized. In any event, a meticulous study of instrument arrangements for use by pilots under high g-conditions is considered essential to the success of piloted entries.

CONCLUDING REMARKS

On the basis of the studies briefly summarized herein, it is felt that entries into the earth's atmosphere which require prolonged periods of several minutes at moderate to high levels of deceleration can be satisfactorily accomplished by the average pilot and to not require extensive conceptual or hardware changes. Up to 8g, positive normal or positive longitudinal, conventional seating facilities with few minor modifications will be satisfactory. If variable lift capabilities are combined with high drag, entries at circular satellite velocity at flight path angle up to $(-)6^{\circ}$ can be accomplished without exceeding 8g.

Range control with vehicles having high-drag variable-lift characteristics appears to be quite feasible. However, the methods studied are dependent upon the availability of acceptable position measuring devices.

(Typed 4-6-59, lb)

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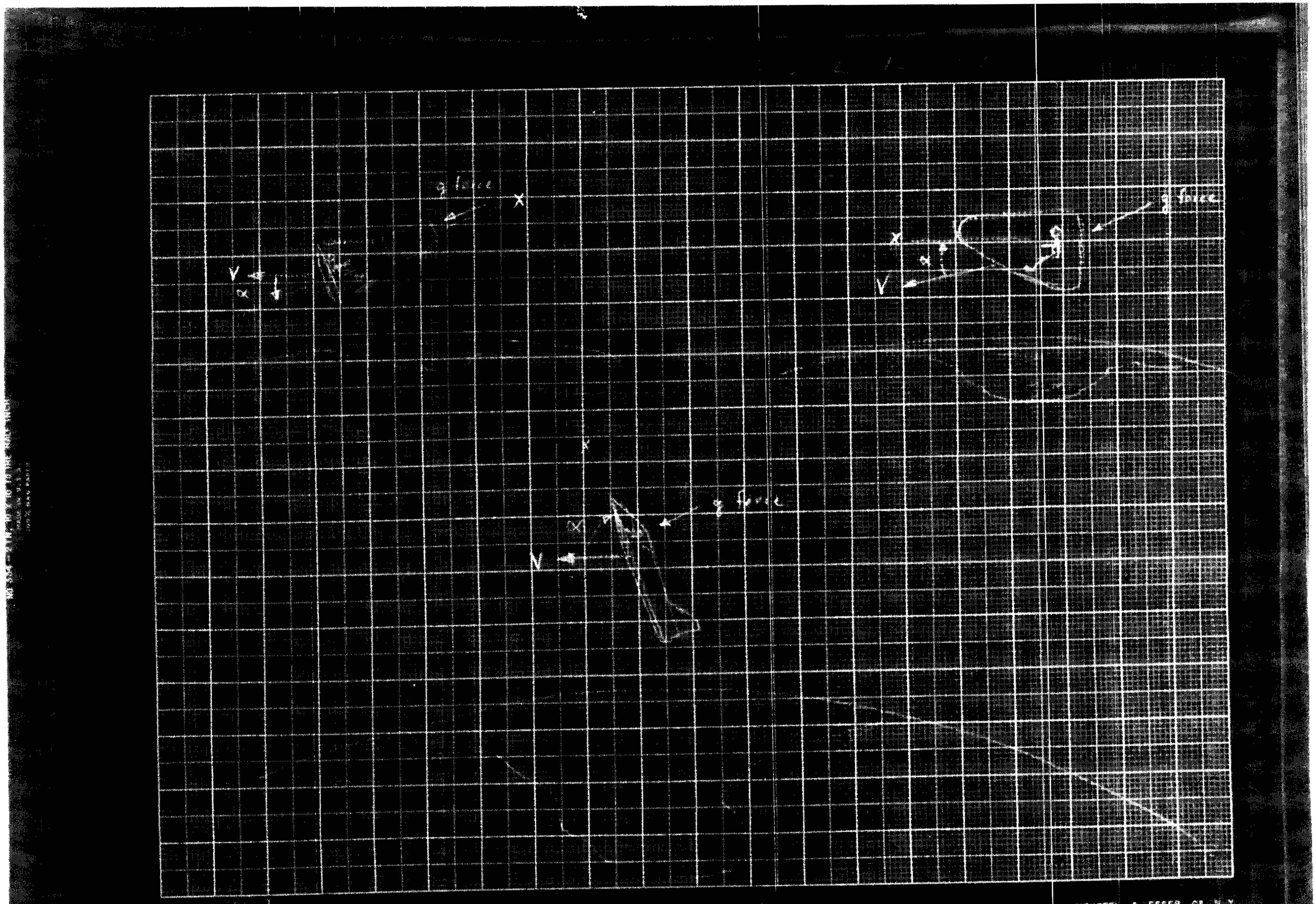

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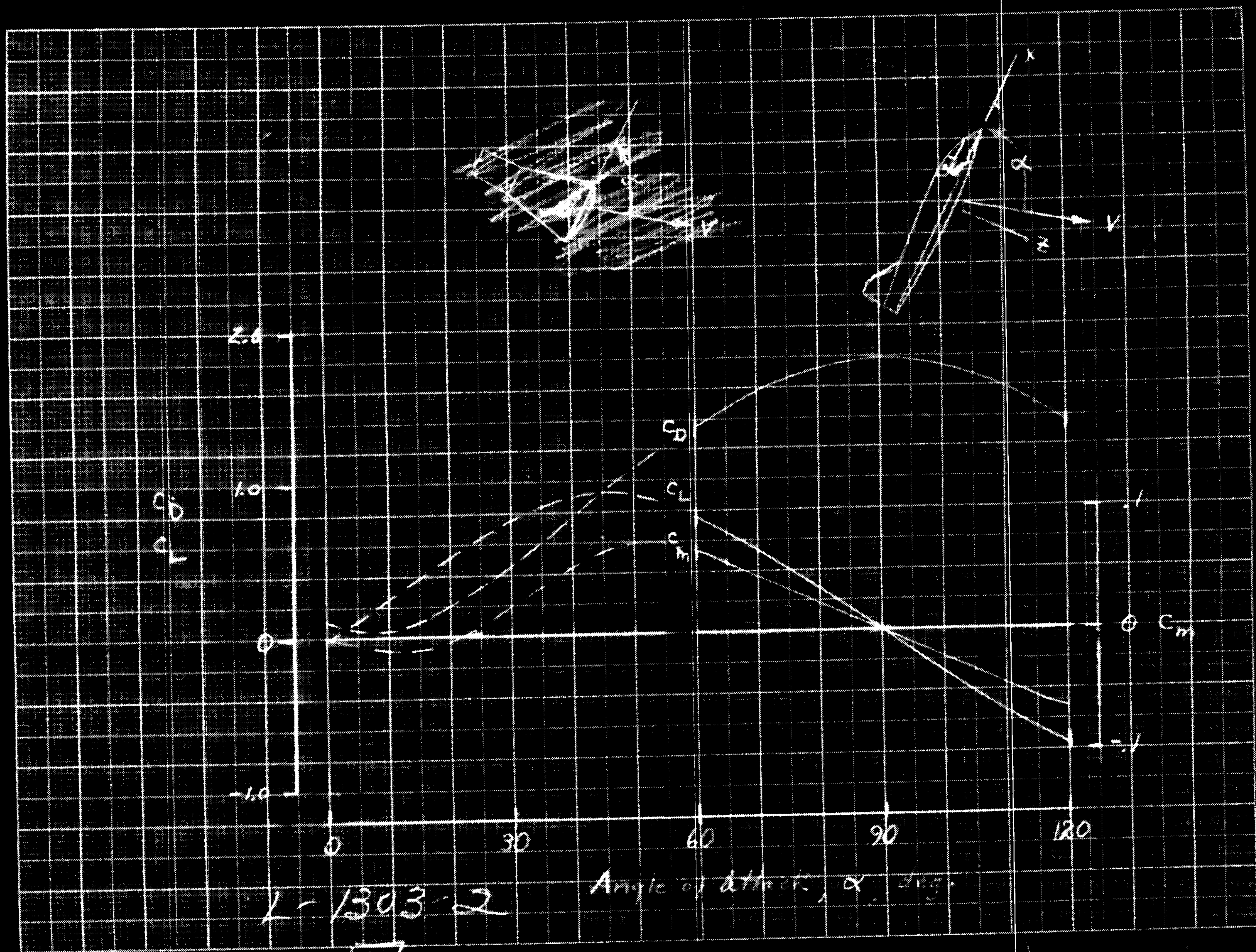


Figure 2 Drag

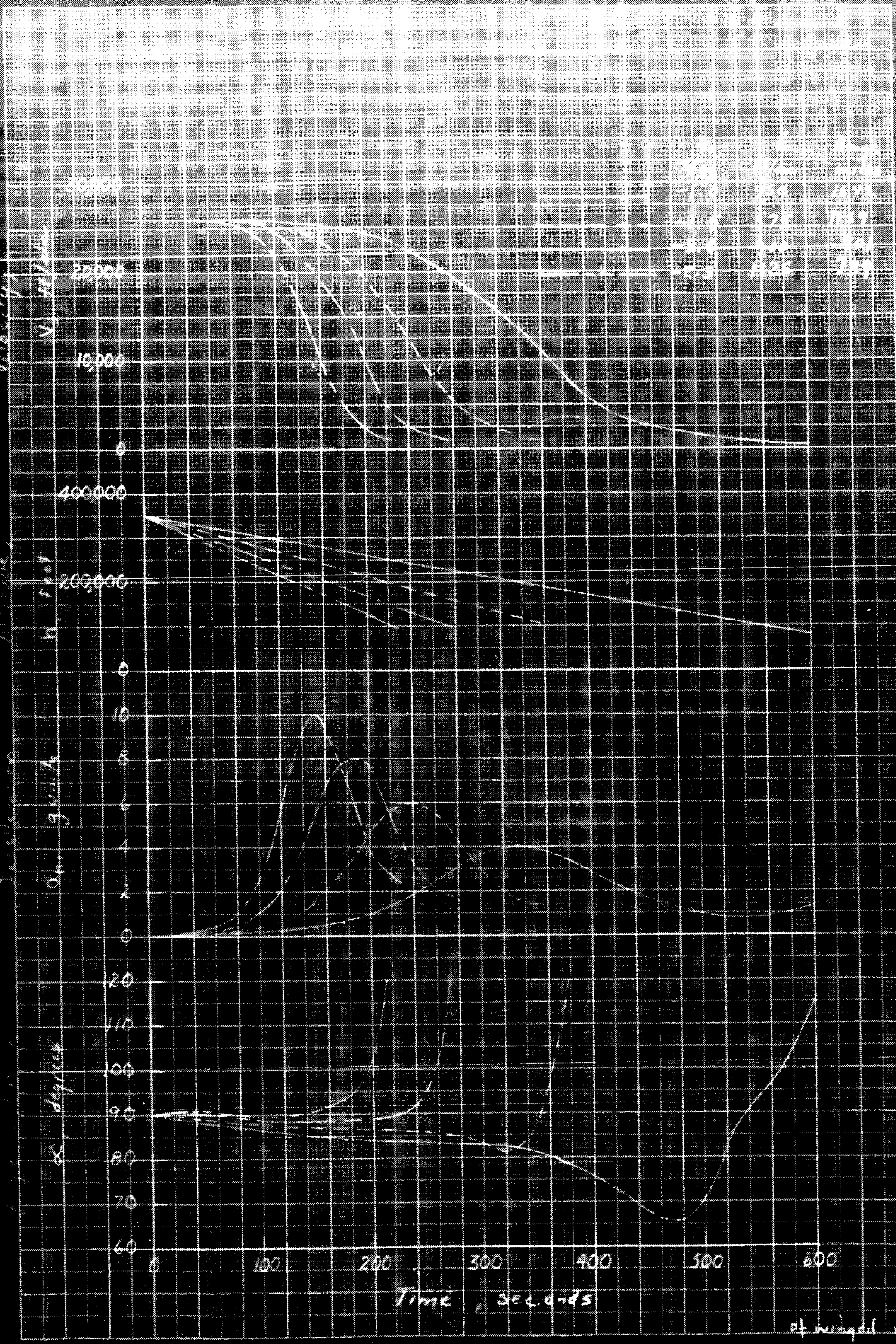
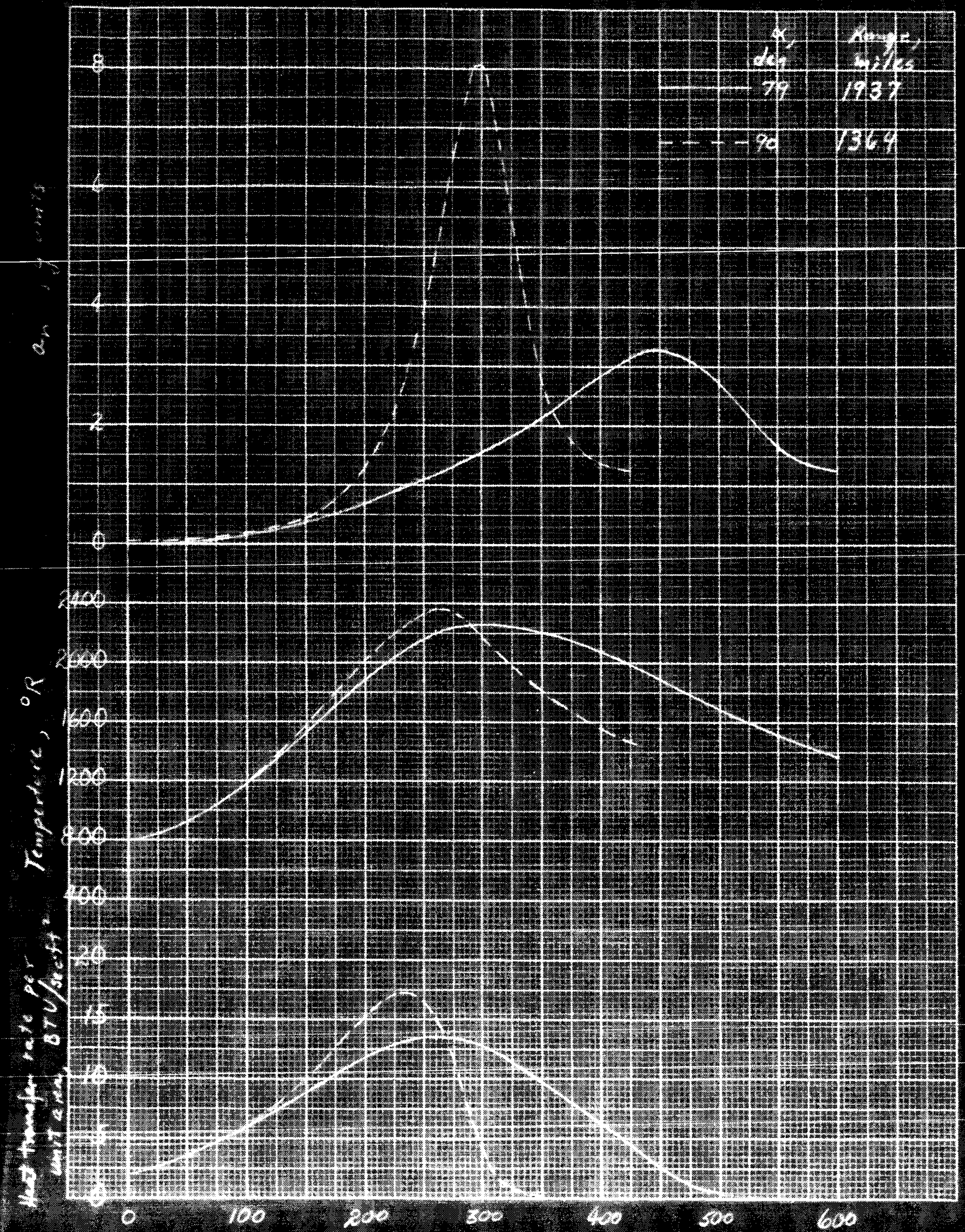


Figure 3 Trajectory data for entry into the earth's atmosphere of winged vehicle at a constant rate of descent. Rates of descent determined from initial flight ~~path angles~~ with $V_0 = 25,863$ ft/sec, $h_0 = 350,000$ ft/sec

only

L-1303 -



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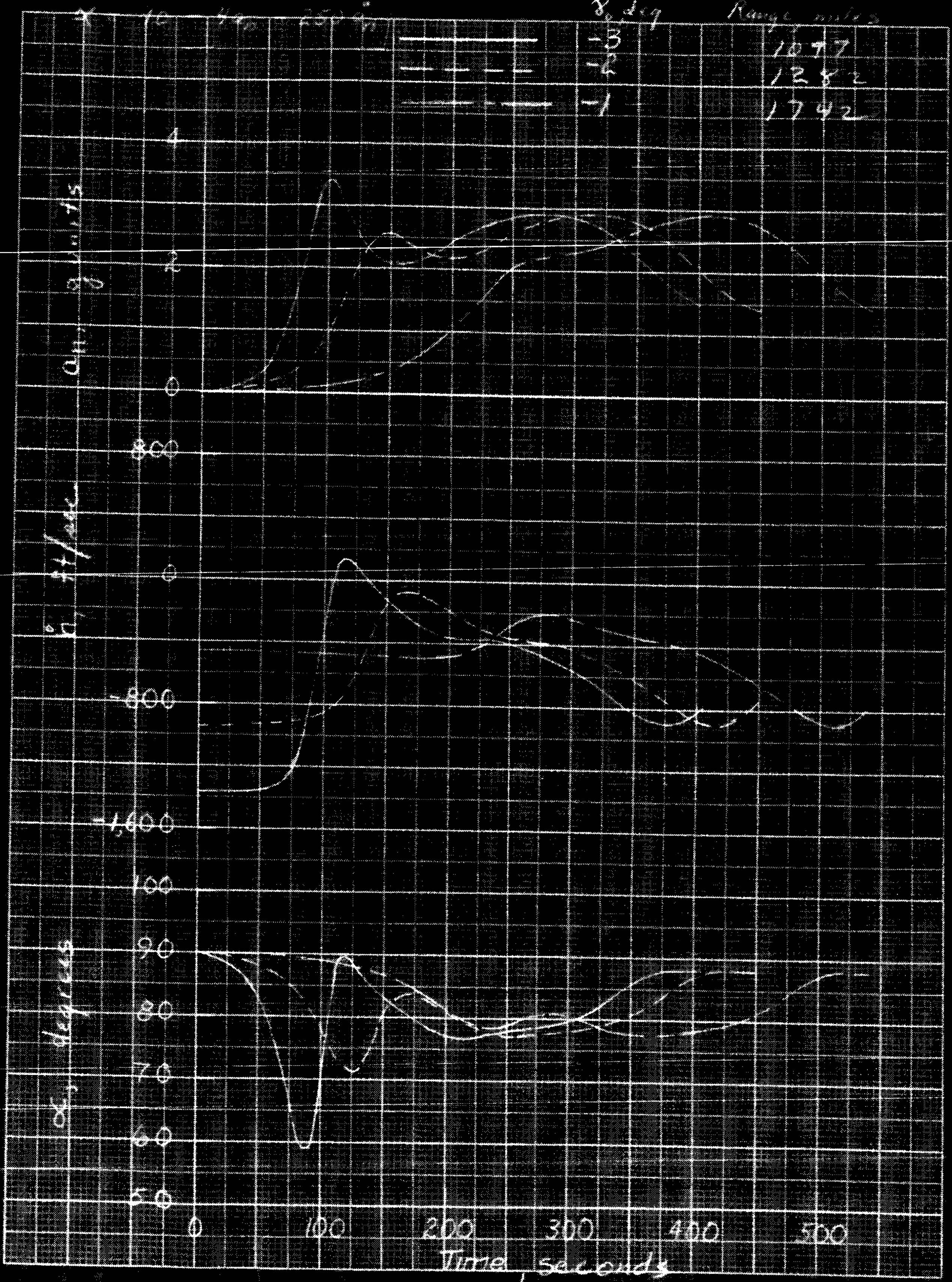
14 Two Constant angle of attack Trajectories

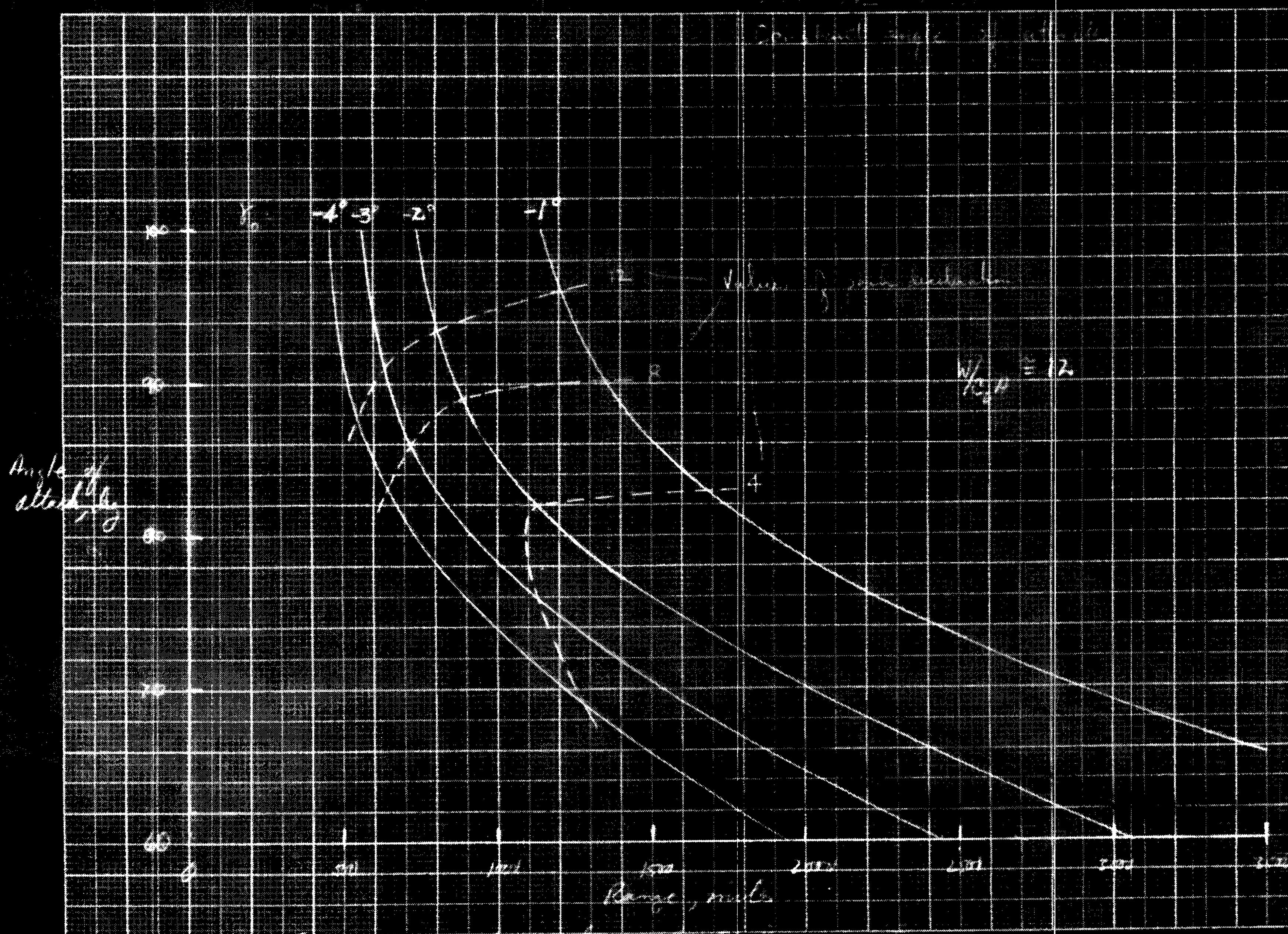
Figure only L/D = 0 and .194, h_0 = 350,000 ft, γ = -1 degree, v_0 = 25,863 ft/sec



γ_0, deg
Range, miles
-3 1077
-2 1282
-1 1742
a_H, g units
4
2
0
800
0
-800
-1,600
$\dot{h}$, ft/sec
100
90
80
70
60
50
α, degrees
0
100
200
300
400
500
Time, seconds

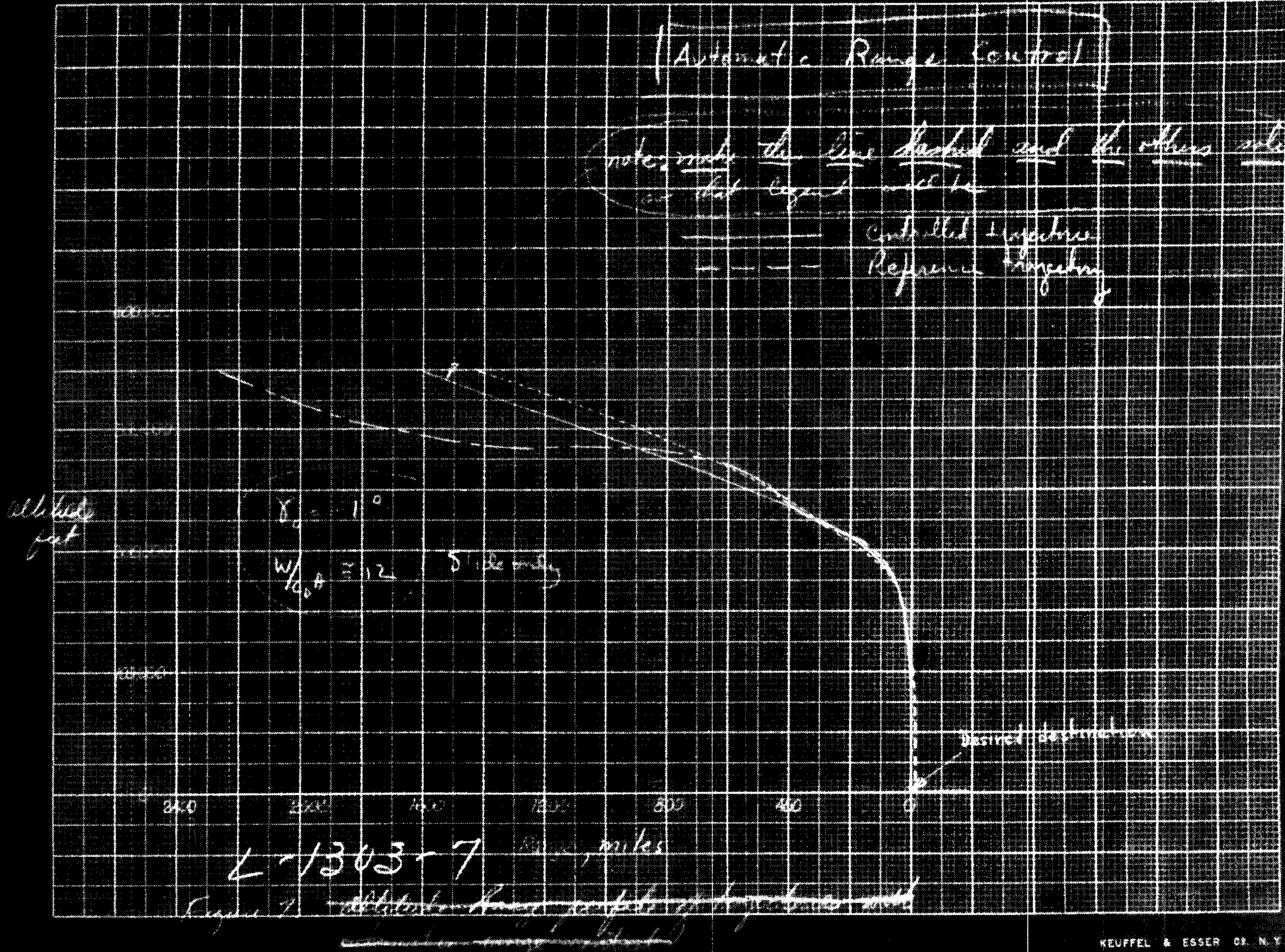
5

L-1303-5



γ_0
-4°
-3°
-2°
-1°
12
8
4
$W/C_D\rho$ = 12
Angle of attack
0
500
1000
1500
2000
2500
3000
3500
60
70
80
90
100
Range, miles
KEUFFEL & ESSER CO. N.Y.

L-1303-6



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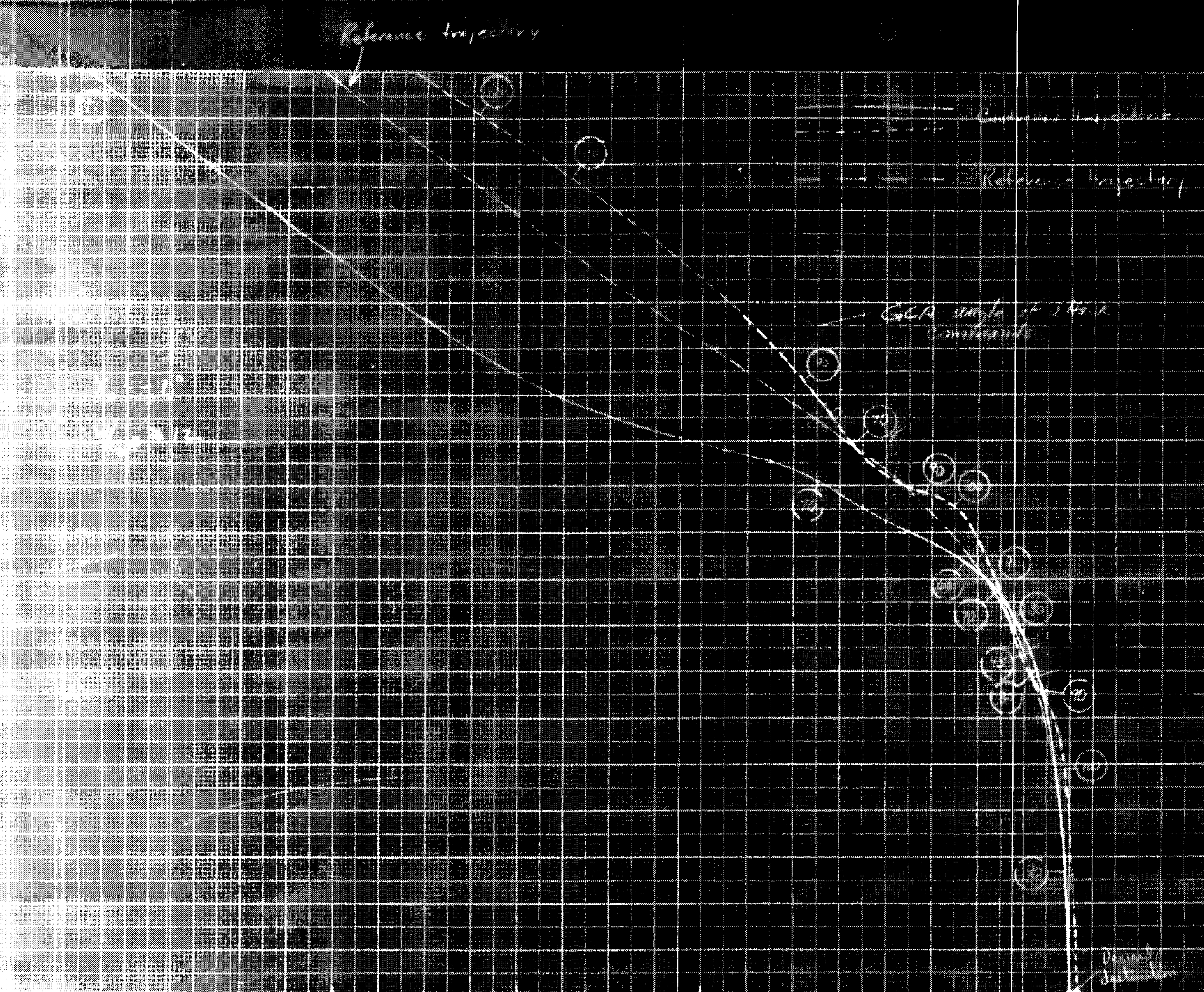
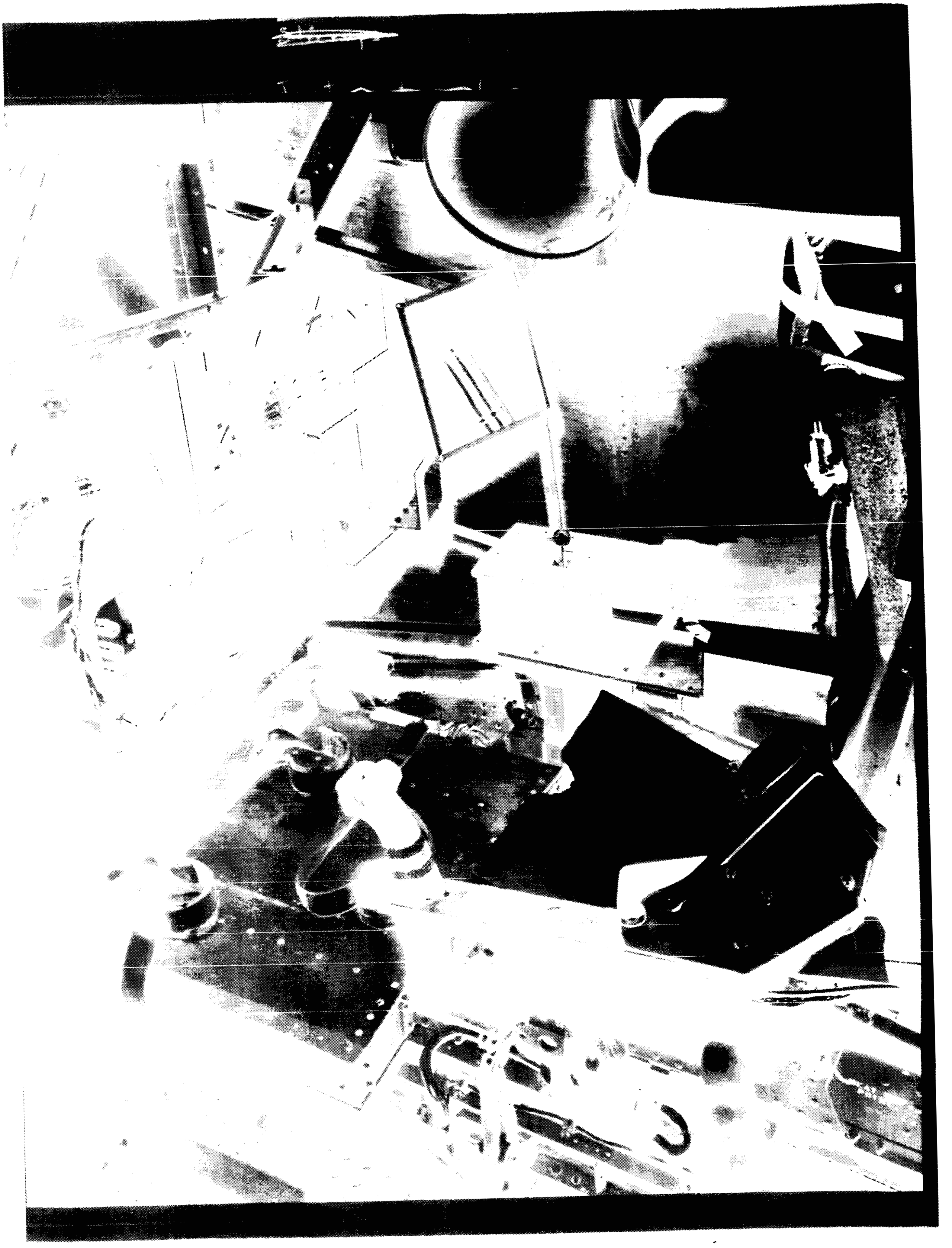
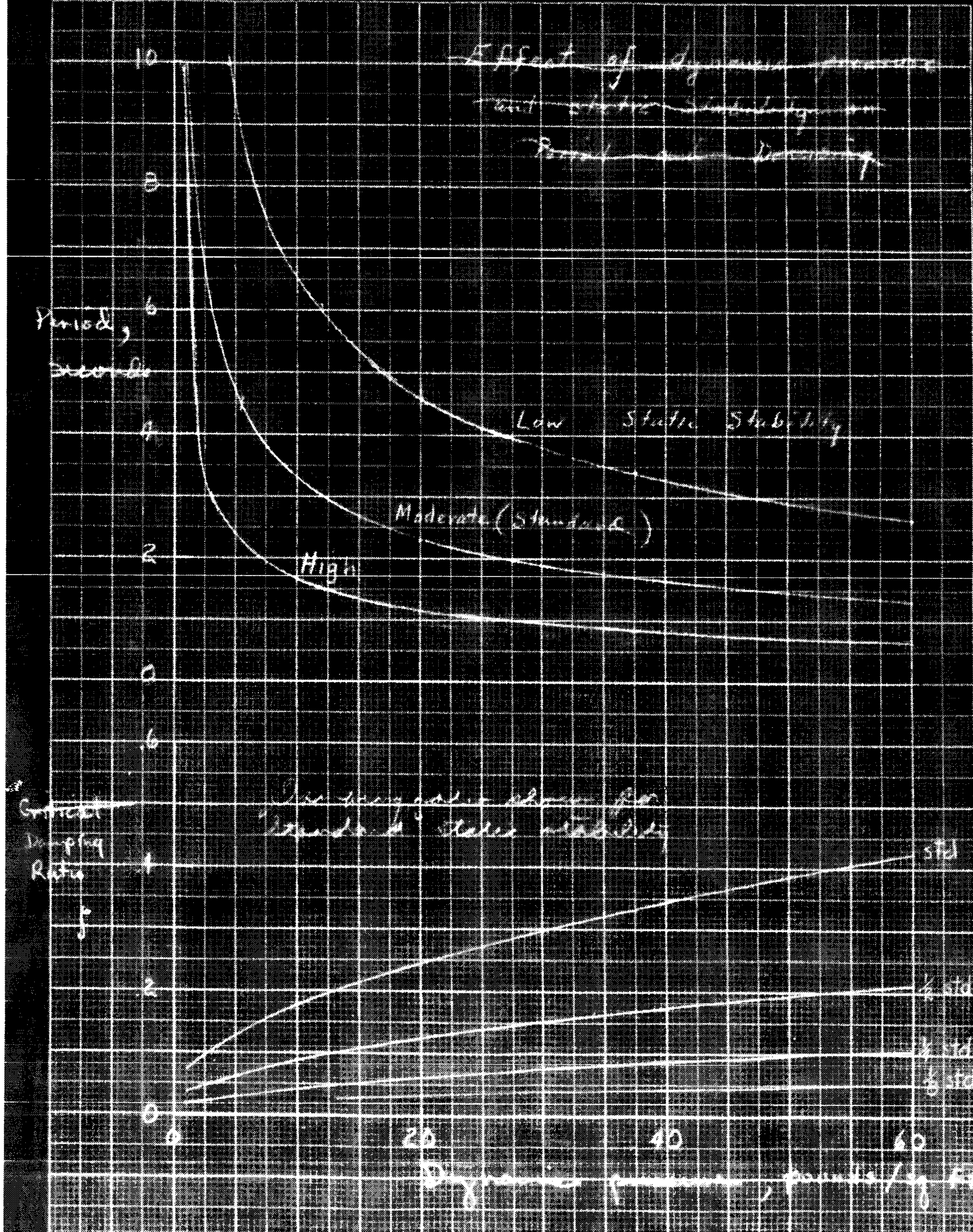


Figure 9 Simulated trajectories controlled by commands from a ground station L-1303-9





Slide 11 Variation of Period and Damping with dynamic pressure
L-1303-11

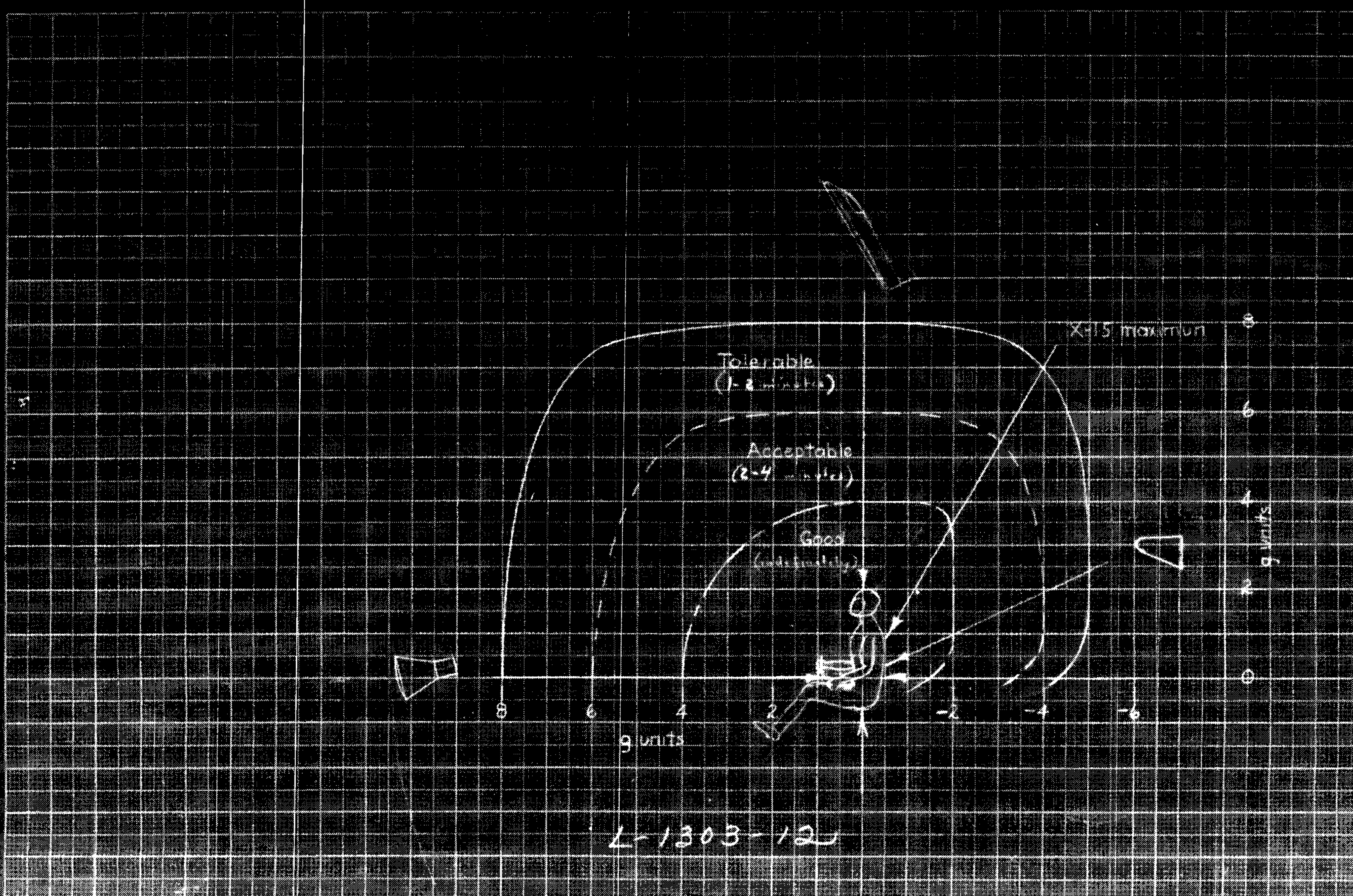


Figure 12 G tolerance fields